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ABSTRACT

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AFHRL-TR-74-65

SOME CONSIDERATIONS IN THE DESIGN AND UTILIZATION OF SIMULATORS FOR TECHNICAL TRAINING

By

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August 1974

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The current technical literature, as it relates to simulators, training devices, and simulation in technical training is reviewed. Rules and principles for the cost-effective application of simulation are also included. A major finding is that fidelity can be quite low in certain procedural tasks without a decrement in performance.

Other studies indicated that some complex electronic equipment can be simulated in simple, relatively inexpensive devices without having an adverse effect on training.

In general, very few studies have been completed to validate the rules and principles of simulation that were developed over 20 years ago.

SUMMARY

Problem

In view of the many successful applications of simulation in flight training, Air Force training experts have proposed that an expansion of the use of simulation in technical training might produce similar results. Research has demonstrated that low-cost/low-fidelity simulation techniques used in some tasks can provide training equal to or better than training using expensive simulators or operational equipment. The extensive use of operational equipment for training has proved to be expensive and inflexible in many training situations. Among the advantages of using simulation are: (a) capability for malfunction/emergency practice, (b) time control, (c) increased feedback, and (d) an opportunity to practice difficult and expensive operations. Thus, the present study was designed to evaluate the requirements for, and the use of, low-cost simulation techniques for technical training.

Approach

The technical literature on simulators, training devices, and simulation in technical training was reviewed covering the last 20 years. Some of the review topics covered were definitions of simulation; types of simulators; the uses of simulation, fidelity, transfer of training, learning taxonomies and simulator design; task analysis; stages of learning; and guides and handbooks involving training device and simulator design. The principles and rules known for the application of simulation are also discussed.

Results

New research, that concerned the evaluation and application of low-cost/low-fidelity simulation techniques, was discussed in detail. Several studies were discussed that demonstrated that for certain procedural tasks, the fidelity of a training device can be quite low without having any adverse effects on measures of criterion performance. Other studies pointed to the fact that the operation of complex electronic equipment may be simulated in simple, relatively inexpensive devices without any decrement in training.

Conclusions

Most of the systematic compilations of rules and principles governing the cost-effective use of simulation were developed during the early 1950s. Although there have been applications of simulation in technical training over the past several years, only a few of the studies have attempted to use a cost-effective approach based upon previously developed rules and principles. In general, the methodologies that have been developed for the application of simulation have been long and cumbersome. Attempts at validating rules and principles have been relatively rare, and, as a result, little more is known now about the application of simulation in technical training than was known 20 years ago.

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SOME CONSIDERATIONS IN THE DESIGN AND UTILIZATION OF SIMULATORS FOR TECHNICAL TRAINING

I. INTRODUCTION

Over the last decade, Air Force weapon systems and their associated equipment have increased in complexity at an extremely rapid rate. This increase in complexity has produced a corresponding increase in the demand for highly trained technicians to operate and maintain these sophisticated systems. To meet the demands for cost-effective, quality-oriented training, simulators have often been proposed as alternatives for expensive, non-flexible operational equipment that is often used for training. The general purpose of this paper is to review the uses of simulation in technical training with special emphasis on relatively inexpensive simulation, and to develop some guidelines and general principles for using such simulation.

This report contains five major sections: Simulators and Training Devices, Simulation in Technical Training, Fidelity, Planning for Simulation, and Principles of Simulation. The first section deals with definitions of simulators and training devices and the types of training devices. The need for, and uses of simulation are discussed in "Simulation in Technical Training." The next section deals with fidelity and transfer of training. Under "Planning for Simulation," methods of task analysis are discussed along with various guides and handbooks. The report concludes with a review of selected guidelines and principles of simulation.

Literature covering the use of simulators and training devices in areas related to technical training is reviewed. This review covers the period 1950 to the present with special emphasis on 1950–1960. This period has been emphasized because much of the pioneering research, both theoretical and applied, was conducted then. During the first 10 years, much of technology related to systems approaches to training was being formulated and adapted to field usage. Training devices were being developed for technical training, and methodologies for using training devices/simulators were being devised. Over the period of the last 10 years or so, only scattered applications of the theories developed during the 1950–1960 time period can be discovered in technical training. The most significant recent developments relate to gaming and computer modeling of systems. While these developments are important, the emphasis of this paper will remain on simulation as it applies to technical training in the Air Force today.

Sources Searched

Relevant literature was identified from a search of the following sources: psychological abstracts, and specific report bibliographies requested from the Defense Documentation Center (DDC). The greatest emphasis was placed on literature identified and received from DDC. Descriptors used for the DDC search were: simulators, training devices, simulation in technical training, training, industrial training, and systems analysis. In addition, books and appropriate journals were identified and examined as a result of reviewing previous sources.

II. SIMULATORS AND TRAINING DEVICES

Definitions of Simulation

Although the concept of simulation has a long military history, a common definition has not yet been agreed upon. As a result, a great diversity of equipment has been tagged with the term "simulator." One definition by Gagne (1954) states that "a simulator is generally understood to be a kind of training device which has a high degree of resemblence to operational equipment, particularly with respect to the display, the controls, and the way one affects the other when in operation." Gagne (1961) elaborated on the foregoing definition by defining all true simulators as having three things in common: (1) an attempt to represent a real situation in which operations are carried out, (2) a provision for certain controls over the situation representing the real operational situation, and (3) a design that deliberately omits certain parts of the real operational situation. Taking a similar viewpoint, Kinkade and Wheaton (1972) state that a simulator is a highly complex training device that attempts to reproduce a large number of the operational characteristics of a system and includes the system's response to control actions.

A more detailed definition of simulation is reported by Baker and Warnick (1970). Their definition refers to simulation as "the technique of

systematically abstracting and partially duplicating a phenomenon, activity, or operation to effect: (a) the design of a system in terms of certain conditions, behaviors and mechanisms; (b) the analysis of a specific phenomenon, or (c) the transfer of training from a synthetic environment to a real environment." Baker and Warnick further state that the above definition implies three objectives of simulation: design, analysis, and training. They also state that there are three models of simulation involving physical, symbolic, and operational mock-ups. The three models described are not necessarily independent since any simulation program may use any combination of the three models or the three objectives stated.

Although there have been many definitions of simulation, some researchers prefer not to use the term at all. Miller (1953a) argued that the term "simulator" was so vague, and often misleading, that he preferred not to use it. Miller concluded that any "simulator" simulates only to a certain degree. Thus, the design and construction of simulators involves a process of selection and decision. Both Miller (1953a) and Gagne (1954) agree the mixture of engineering and psychological terminology has caused confusion in the definitions surrounding simulation. Miller states that there are major distinctions between engineering and psychological definitions of simulation. He defines engineering simulation as "the duplication of physical and functional characteristics of operational equipment within very tight tolerance specifications. These tolerances are usually close to the limit of engineering skill and often beyond those of production capability." Psychological simulation differs to the extent that "one situation simulates another when the subject or operator transfers to the second situation (with zero decrement) the responses he has learned or performed in the first situation." Miller emphasizes that psychological simulation should be given preference in the design of training devices, since it produces the greatest economy and maximum validity in training.

Definitions of Training Devices

A similar confusion exists about the definition of a training device and the difference between such a device and simulators. The critical differences between the two is often conceptualized in terms of their relative functions. Kinkade and Wheaton (1972) feel that the broad purpose of a simulator is to provide conditions which facilitate learning. A similar definition of the broad purpose of simulators and training devices is provided by Gagne (1961). He suggests that a simulator has a very specific purpose, whereas a training device has a more general training purpose. Therefore, it is often the design for task or job specialty that differentiates between a simulator and a training device.

Although there has been some disagreement over terminology, simulators are typically thought of as being a subset of the general class of training devices. Biel (1965) feels that a simulator is in a special class of training device which attempts to reproduce or simulate the essential tasks of an operator or operators. In general, a training device is thought of as any apparatus that is used in the training of individuals. A more precise definition is provided by Lumsdaine (1960). He states that "a training device is any arrangement of equipment, components, apparatus, or materials which provides conditions that help trainees learn a task." Gagne (1954) simply states that a training device is "any apparatus that is used for the training of skills." Consequently, a simulator normally reproduces a job or some element of a job to a fairly high degree, whereas a training device may be used to train a more general function, such as a concept related to the performance of a job. In other words, a trainer may not necessarily be used to train students to perform an actual job task. Simulators are, however, normally job specific.

Types of Training Devices

Training devices consist of two general categories: training aids and training equipment. Kinkade and Wheaton (1972) distinguish between training aids and equipment by defining training aids as devices used by an instructor to help him present subject matter. Training equipment differs in that some form of active participation is usually required by the student. Examples of training aids are wall charts, transparencies and slides, motion pictures, closed-circuit television, cutaway mock-ups, operating mock-ups, nonoperational mock-ups, and animated panel displays. Training aids such as the ones just described are usually most helpful in the classroom as supplements to lecture material or for group demonstration purposes. Biel (1964) contends, however, that training aids such as the above are insufficient when more than several trials are required to learn a particular knowledge or skill.

Training equipment can be further divided into two general classes: whole task trainers, and part task trainers (see Figure 1 for a breakdown of the various classes of training devices).

Figure 1 **Classes of training devices.** *(adapted from Kinkaide & Wheaton, 1972)*

Part task trainers, as their name implies, teach a student to perform some segment of a total job task. An example of a part task trainer would be the soldering trainer used by Precision Measurement Equipment (PME) students at Lowry AFB, Colorado. This trainer provides practice on only one segment of the the larger tasks of the PME specialist. The capability for training the larger task of troubleshooting and repair is not provided. Practice on these larger segments of the total task would require a whole task trainer. The issue of whole task versus part task training is discussed by Lumsdaine (1960). He feels that certain prerequisite skills and knowledges can often be separated out from the total task requirements and learned most efficiently using part task trainers. As a general rule, the closer the task is to the terminal stages of learning, the more appropriate a whole task trainer or the operational equipment becomes. Some of the advantages of part task trainers, as collected by Kinkade and Wheaton (1972), are: (1) they are relatively inexpensive, (2) early deliverability, (3) easy modifiability, (4) easy maintenance, (5) that instructors can be more specialized, (6) that training can be more frequent and extensive on a component task, and (7) that the student does not have to divide his attention. Some advantages of whole task trainers are: (1) a greater capability for training since they are less expensive than the number of part task trainers that would be required to perform the same functions, (2) they take up less space, and (3) fewer instructors are needed. The major types of trainers as listed by Biel (1965) are as follow:

1. *Individual trainers*: Trainers that have been developed to meet the need for continued and varied practice.

2. *Automated teaching devices*: Material is usually presented in a fixed sequence that requires a correct response prior to activation of the next sequence of material. These devices can be used to learn routine activities as well as more advanced concepts and principles.

3. *Concept trainers*: Used when the concepts to be learned are too difficult to learn verbally and are best learned from physical representations. The expense of such trainers is considered to be minimal when compared with the cost of using operational equipment.

4. *Games*: Usually used in the area of decision making and planning. There have been extensive numbers of articles, literature reviews, and bibliographies on management games (Davis, 1970; Becker, 1961; Gallo, 1965; Groennings, 1970; Guyer, 1968; Guyer, 1971; McClintock, 1971). Management decision games usually facilitate learning by requiring each participant to actually make decisions and follow up his decisions in a no-risk environment.

5. *Skill trainers*: Used when perceptual motor skills are highly complex. This type of trainer is particularly important when practice on a skill is important and the operational system is not available enough, too sensitive, or beyond the scope of normal operations. Skill trainers also provide knowledge of results, an important consideration that will be discussed later in this report.

6. *Procedures trainers*: This type of trainer consists of a mock-up of an operational station in which the trainee can practice those procedures involved in performing a task. Procedures trainers are also frequently used in transition training from one aircraft or missile system to another. An example of this type of trainer is a missile procedures trainer. Such a trainer has all of the equipment normally present in a launch control center. Students can perform sequences and manipulate dials, etc., to receive realistic indications. Instructor stations are common also and from these stations a wide variety of faults, malfunctions, and emergency situations can be presented to the students.

A somewhat different approach to trainer classification is presented by Miller (1960). Miller defines three classes of trainers as follow:

1. *Familiarization trainers*: The two types of familiarization trainers discussed by Miller (1960) are demonstrators, and nomenclature and location trainers.

Demonstrators: Provisions are made in this type of trainer to develop a concept of the purpose of the man-machine system and its associated processes through displays and words.

Nomenclature and location trainers: In this type of trainer, the student learns to name and locate objects or signals that are part of his work environment. An example is the subject matter trainer that was developed at the Maintenance Laboratory, Air Force Personnel and Training Research Center (deactivated 1958). The device was designed to provide the opportunity for individual and group study of maintenance checks and adjustments. Two types of learning problems are presented by the device: paired-associate learning and serial learning. By using such a device, students may solve problems involving pictorial, schematic, symbolic, or verbal materials.

2. *Instructed-response trainers*: As a general class of trainers, they are most useful when the trainee uses symbols to process environmental inputs in order to make output responses. Miller considers this class of trainers to be the major promise for cheap, but effective training. One advantage of instructed-response trainers is the frequent generalization to widely different situations from those practices. The types of instructed-response trainers follow:

Detection of condition trainers: The trainee learns to detect the presence or absence of signals or cues in his work environment. This ability is important for learning scanning techniques.

Identification of conditions trainers: The student practices selecting and then bringing together different display elements in order to identify an object or state of affairs.

Problem-solving and decision-making trainers: In this type of trainer, the trainee must identify a complex set of conditions and then make a decision to perform some action as a result of this identification. An example is the malfunction and circuitry trainer for electronic troubleshooting.

Instructed-response trainers for procedures: Trainees learn sequences of displays and relationship between controls and displays. The object is to establish errorless responses, but these responses do not have to be quick, smooth, or coordinated. An example of this kind of trainer is a flight engineer panel mock-up.

3. *Automatized skill trainers*: In this class of trainers, the trainee has progressed to the level that skills and many complex activities are automatic. Skill trainers must bear a strong physical resemblence to the real equipment world, making the term simulation more appropriate. This physical realism is especially important in tracking tasks. The types of automatized skill trainers are as follow:

Tracking task trainers: A more-or-less continuously graded response is required to more-or-less continuously changing stimulus conditions. The trainee learns to anticipate dynamic target motions and to anticipate the performance of the cursor under his control from given control inputs. Most examples of this type of trainer are found in aircraft simulators.

Job segment trainers and simulators: Most of this type of equipment is full simulation of a segment or a whole job. The work environment and working conditions are replicas of the real operational situation.

III. SIMULATION IN TECHNICAL TRAINING

Need for Simulation

The need for simulation in many technical training courses is prompted by several common training problems. One problem, as mentioned earlier, has been the use of operational equipment, arranged on a bench, for training. The use of this equipment has often been a carryover from the days when electronic equipment was relatively simple and easy to maintain. Today's electronic

equipment is, however, much more complex and sophisticated. As a result, using actual equipment for training frequently proves to be less than satisfactory for several reasons. First of all, the operational equipment is often quite expensive to buy and maintain. The high maintenance expense is primarily the result of the equipment not being rugged enough to sustain the kind of abuse common to the typical training environment. Another important factor that can influence the effectiveness of operational equipment used for training, is the difficulty for fault and emergency situation insertion by the instructor. With this capability for insertion of various faults, emergencies, etc., students can practice problems they are likely to encounter in the field or be evaluated on critical operations or emergencies that are too sensitive to be performed on operational equipment. As a result, many critical operations that are important to operational effectiveness are not practiced or evaluated in training. Additionally, the classroom instructor is often faced with the problem of what to do with the remainder of the class when one or several students are practicing or being evaluated on operational equipment. Serious obstacles to effective training can arise since training equipment is usually too expensive to purchase in large enough numbers to accommodate an entire class. This problem could also exist when simulation is used. However, inexpensive simulators could be made available in larger quantities and, thereby help to alleviate the problem of scarce training equipment. Another obstacle is that the operational equipment has no self-instructional capability. In other words, there is no provision in the equipment to guide a student through an instructional sequence when the instructor is not available. Thus, as stated by Briggs (1955), "some other maintenance training equipment . . . is apparently needed to supplement use of operational equipment in order to make maintenance training more effective."

Even though simulation can often solve many of the problems associated with using operational equipment, other factors suggest that full-fidelity simulation may not be cost-effective. As pointed out by Miller (1953a), there is a relationship between the degree of engineering simulation, cost, and transfer of training value. The relationship between these variables is such that as the degree of engineering simulation increases, a point of diminishing returns may be reached between costs and transfer of training. Thus, producing a high-fidelity simulator may not produce the most training value for the dollar cost (Figure 2).

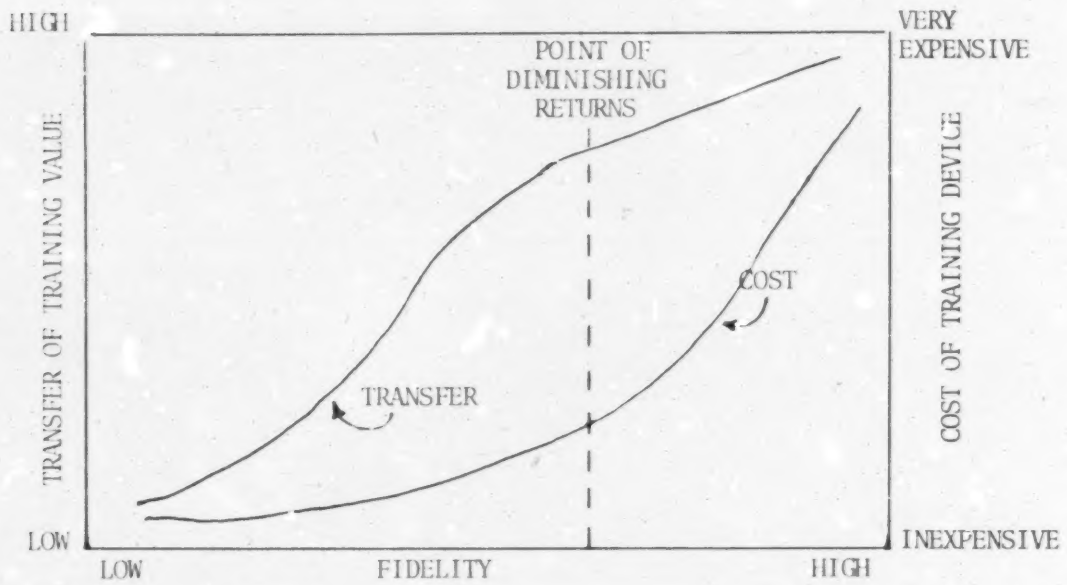

Figure 2. **Interrelationship between cost, fidelity of simulation, and training effectiveness.** *(This fig. is adapted from Miller, 1954.)*

A further rationale for using simulation is provided by Baker and Warnick (1970). They identify eight reasons for the use of simulation: (1) compensating for or duplicating an unusual environment, (2) the systematic collection of information about a process, (3) breaking down complicated and unmanageable systems into less-complicated subsystems, (4) gaining understanding to facilitate decision making, (5) an inexpensive way to study, test, or experiment with a proposed innovation, (6) a vehicle for revealing the significant variables in a system and how they are related, (7) time compression and expansion, and (8) providing information about some of the unknown consequences of innovations.

Thus, simulation can be quite useful under certain circumstances where the real world cannot be controlled or manipulated. In many systems, there are critical and emergency situations that for obvious reasons cannot be practiced or evaluated on operational equipment. Simulation provides the capability to train and evaluate students on critical and otherwise dangerous situations without any fear of damage or loss of life. Simulation also provides the capability to control time. This factor is highly important in certain operations that are time consuming, highly complex, or when the capability to halt a sequence would be advantageous to the training process. In such cases, the student can see the results of his actions immediately without waiting for intervening time-consuming steps to take place. The student can also run through a highly complex operation step by step at his own rate, and in certain cases, an operation or sequence can be stopped to analyze what has occurred in order to facilitate learning. Other obvious uses of simulation occur when expensive hardware or operations must be tested or exercised. Using simulation can provide all of the realistic system responses without the expense and danger of using operational hardware.

Some of the advantages for using simulation, as discussed earlier, are reported by Lumsdaine (1960). He feels that training devices and/or simulators are often the best alternative to using operational equipment when such equipment is scarce, nonexistent, under development, expensive, and where training on the operational equipment may be hazardous to personnel and possibly damaging to the equipment. Another advantage of simulation devices as opposed to operational equipment is the capability for feedback so that errors can be prevented, corrected, and reported efficiently. Trainers can also concentrate on crucial job operations. Trouble-shooting often requires training on malfunctions that rarely occur on operational equipment. Trainers also permit the operator to perform functions that are difficult to reach, are time consuming, and are dangerous and expensive to perform on operational equipment. Trainers can also make operations visible for study, and provide the opportunity for students to practice operations that might be too costly on the operational equipment. Other researchers, such as Parker and Downs (1961), emphasize the motivational and instructional advantages of simulation. They discuss four basic reasons why simulators are needed. First, simulators provide an opportunity for correct response. The operator can have the advantage of practicing all of the required response actions of a system. Next, the simulator can provide guidance toward the correct responses. Since the operational equipment cannot provide guided-response actions, the simulator possesses the considerable advantage of permitting a trial-and-error method to be followed by the student. Another important advantage is knowledge of results. In this respect, a simulator can provide the important advantage of feedback, which is crucial to the learning performance of a task. Finally, the simulator can often provide an inherent motivational quality for students.

AFM 50-2 lists four reasons why simulators can be effective instructional devices:

1. Provisions are made for active student participation.

2. There can be repeated practice on instructional segments.

3. Instruction can be paced to the needs of the individual student.

4. The accuracy of student response can be confirmed.

It appears that a fairly comprehensive compilation of the reasons for using simulation would consist of the basic instructional capabilities listed by AFM 50-2 and the advantages of malfunction/emergency practice, and training equipment availability.

Research Program

In order to resolve some of the problems associated with operational equipment and high-fidelity simulators for technical training, the Air Training Command requested that the Technical

Training Division, Air Force Human Resources Laboratory, Lowry Air Force Base, Colorado design a program of research to investigate cost-effective simulation. Cost-effective, or low-cost simulation, is defined as a wide range of simulators/training devices that are relatively inexpensive to produce due to tradeoffs between engineering similarity and transferability. It is also assumed that cost-effective simulation will provide training that is at least as effective as training devices that use expensive operational or full-fidelity equipment. Miller (1960) agrees by stating that simulators push for 100% transfer. He further states that practice on a simulator should be equal to or superior to using operational equipment. This selective review of simulation in Air Force technical training is part of a comprehensive program to evaluate the requirements for, and the use of, low-cost simulation training devices in technical training. An additional purpose of the research effort is to develop a methodology, or procedure, that will define where simulation can be used effectively in technical training applications.

Uses of Simulation

The use to which a simulator is put is perhaps more important than the actual design of the simulator. As sometimes happens, a simulator is built to simulate a particular aspect of a system and proves to be inadequate because it was built without proper attention to its intended purpose. Three purposes of simulation are discussed by Gagne (1961). First, simulators are used extensively for training. Perhaps the widest use of simulators is in pilot training by the military and commercial aircraft companies. The complexity and specificity of simulators usually dictates that they be used rather late in usual training cycles. For this reason, simulators are typically employed to consolidate and maintain skills rather than for initial acquisition of skills.

Another purpose of simulation is assessment of proficiency. Simulators used for this purpose often resemble simulators that are used for training. The only real difference may be in the degree of task difficulty for the student. In measuring proficiency, it is often necessary to present a student with a very difficult or very unusual situation to test the degree to which the skill being measured has been obtained.

The third related purpose of simulation is the development of operational doctrine. Simulators have proven to be highly effective in developing doctrine in weapon systems that are highly complex or too expensive to operate. The simulator used for this purpose can provide an analyst with step-by-step systematic information about how a weapon system could be utilized.

IV. FIDELITY

Fidelity of Simulation

In its broadest sense, fidelity refers to the accuracy of reproduction involved when an attempt is made at such reproduction. Thus, fidelity would imply the degree to which a simulator resembles the real operational equipment or situation. However, as was stated by Gagne (1954) and Biel (1965), simulation itself implies some departure from reality since it represents an abstraction of reality.

Since it has been hypothesized by Miller (1953a) that the cost of simulation rises as a function of fidelity, the question becomes one of determining how much fidelity is necessary without degrading the value of the training received by a student. Or more specifically, at what point does simulation cease to be cost-effective. As discussed earlier, cost-effective simulation is thought of here as a wide range of simulators/training devices that are relatively inexpensive to build and maintain due to tradeoffs between engineering fidelity and transferability from the simulated job environment to the operational environment. Thus, it becomes necessary for those charged with making training equipment procurement decisions to determine what elements in the operational situation should be represented and with how much fidelity. Biel (1965) lists two aspects of simulation that must be considered to determine the degree of fidelity required in simulation: (1) what equipment and functions must be simulated, and (2) how accurately the stimulus situations on which training is being given must simulate real life.

According to Kinkade and Wheaton (1972), fidelity of simulation consists of three different components: (1) equipment fidelity, (2) environment fidelity, and (3) psychological fidelity. Equipment fidelity is defined as the degree to which the simulator duplicates the appearence and "feel" of the operational equipment. Environmental fidelity is conceived of as the degree to which the simulator duplicates the sensory stimulation in the task situation. Sensory stimulation, in this case, does not refer to control feel, which is included in equipment fidelity, but, instead, to the dynamic motion cues and visual

presentations that would appear similar to the real world. This type of fidelity can be especially important in flying training and driver training. Psychological fidelity is simply the degree to which the trainee perceives the simulator as being a realistic duplicate of the operational equipment and the task situation. Psychological fidelity impacts significantly on the other two components of fidelity with respect to cost savings. Often the equipment and environment fidelity can be reduced simply because the human operator is not capable of perceiving or discriminating levels of fidelity in visual or motion cues. When this is the case, the lower level of fidelity could prove to be much less expensive to produce and be equally as effective.

Tilden (1962) describes degree of fidelity as being composed of two variables: face validity of simulation, and accuracy of simulation. Tilden then discusses how the two components of fidelity can be illustrated with four applications of fidelity as design characteristic. The first application describes presentation of information to a trainee. The implication derived is that information can be conveyed with a high degree of accuracy using low-fidelity simulation that lacks the face validity of high-fidelity simulation. The example given is an out-of-the-window view from a spacecraft. Either elaborate techniques or a simple black line on a white surface could be used to represent the same information. Similar discussions are presented with simulation of operational control mechanisms and vehicle control dynamics, work environmental conditions, regulation of changes in information to be displayed, changes in movement of controls, and changes in environment that replicate real time sequences. In all of the above, there are applications of accuracy that compensate for face validity simulation. Tilden concludes that the degree of fidelity required for equipment design is a consequence of the training objectives and the learning theory underlying training procedures. Learning theory, as referred to here, is related to the objectives of training in such a way that the theory employed will determine the degree of fidelity required for maximum learning and retention. Tilden conceives of learning theory to be composed of such concepts as stimulus, information, perception, feedback, generalization, motivation, transfer, etc., referred to earlier as psychological fidelity. Thus, it seems that as long as the trainee perceives the simulator as being a realistic equivalent of the operational equipment or situation, savings may be realized by reducing fidelity. Gagne also feels that degree of simulation is a secondary consideration to how a simulator is utilized. He views the two uses of simulation as performance measurement and performance improvement. In performance measurement, the important variables are reliability and validity. Whereas, in performance improvement, the important characteristic is transfer of learning to an operational task.

Miller (1953a) views the degree of simulation required as being directly related to the stage of training. In his framework, decisions about fidelity and the degree of simulation are based to a large extent on the stage of learning wherein training is being conducted. The degree of simulation increases as a trainee moves from the highly verbal stages in early learning to the more complicated automatic behaviors that occur later in the training cycle. This direct relationship is hypothesized to continue until a point is reached where additional simulation would not be cost-effective in terms of transfer of training. Much research concerned with varying levels of fidelity had been conducted on procedural and familiarization tasks which occur very early in the training cycle. In general, most of the preceding research has concluded that fidelity can be held to a minimum in procedural and familiarization tasks without having any adverse effect on student performance and transfer of training. Research has thus tended to substantiate the relationships between fidelity, stages of learning, and transfer of training set forth by Gagne and Miller concerning the early stages of learning.

Fidelity and Transfer of Training

As was referred to earlier in Figure 3, Miller (1953a) hypothesizes a relationship between simulator cost, transfer of training, and degree of fidelity. In this theoretical relationship, the cost and transfer functions increase as fidelity increases. Although there has been some support for Miller's hypothesis, evidence has also been accumulated that refutes his theory. In a recent review by Erickson, Simpson, and Stark (1972), the conclusion was reached that very few studies have been completed which investigated the relationship between fidelity and training value. In many studies, conflicting conclusions were reached as to the relationship between fidelity and transfer of training value. The only consistent conclusion was that high fidelity was never associated with poorer training. In a recent report by the Naval Training Device Center (Analysis of the Transfer of Training, Substitution and Fidelity of Simulation of Training Equipment, 1972), the authors contend that low-fidelity simulation should not be overlooked even though no consistent relationship

has been found between low fidelity and transfer of training. The authors argue that the obvious cost benefits associated with using low fidelity are pressing even if the low-fidelity simulator produces training that is only equal to the higher-fidelity training. The basic conclusion reached was that transfer of training is more of a function of how the simulator was used rather than the degree of fidelity. Many studies have shown that simulation can be very effective in teaching procedural sequences. Parker and Downs (1961) contend that the learning of precedural sequences is the most effective area for the typical simulator. Since procedures training has long been considered an effective area for simulation, several studies were conducted in which the degree of fidelity varied for a procedural task. Grimsley (1969) ran a series of experiments under HumRRO Work Unit RINGER to study the effect of using low fidelity to train men to perform procedural tasks. He also investigated the effect of retention and reinstatement of performance following training on low-fidelity devices. In previous studies, Grimsley had found that students could be trained to operate the SCI console for the Nike Hercules guided missile system, using a very inexpensive photographic reproduction of the console. The proficiency of the low-fidelity group was equally as high as the groups trained, using the operational hardware and a more-expensive simulator. As a result of several studies, Grimsley concluded that, for training men to perform procedural tasks, the fidelity of the training device can be quite low without having any adverse effect on training time, level of proficiency, amount remembered over time, or time to retrain.

Briggs, Besnard, & Walker (1955) developed a procedural simulator that was to be used to supplement practice on the operational equipment. The F-4 Fire Control System simulator was then built for a fraction of the cost of the operational equipment. The low-cost/low-fidelity device was built inexpensively since only check and adjustment functions were simulated. Performance on the low-fidelity simulator was later found to be highly similar to the more expensive, inconvenient, and time-consuming procedures involved with the operational equipment.

Another study (NAVTRADEVCEN TR 458-1, 1959), conducted by the Navy, compared the effectiveness of training devices having varying degrees of simulation of an operational task. The task selected was one-man control over course and depth of a high-speed submarine. Subjects were tested on five simulators varying in complexity from a highly realistic simulator with programmed equations of motion to a rather simple simulator with no motion cues available. The subjects were trained on one of the five simulators and then evaluated on the most complex and realistic trainer. Results indicated that there were no significant differences in the performance of subjects trained on the five different simulators; however, there was a trend towards better performance as a function of simulator complexity. These results further imply that effective training can be provided with a simplified simulator, resulting in significant cost savings and no loss of training effectiveness.

Cox, Wood, Boren, and Thorne (1965) studied the effects of reduced fidelity on twelve training devices developed for the Army. Cox et al, discovered no significant differences in trainee proficiency or training time regardless of the functional or appearance fidelity of the trainers.

In a study for the Army, Denenberg (1954) compared the effectiveness of a tank hull trainer and an inexpensive mock-up for learning procedures, nomenclature, and operation of a track and suspension system. Although three lessons are taught using the tank hull trainer (Starting and Stopping Procedures, Driver's Instruments and Controls, and Track and Suspension System), only the first two procedures could be taught using the inexpensive mock-up. The results established that the inexpensive mock-up was (a) superior for teaching procedures, (b) equally effective for learning nomenclature, and (c) the tank hull trainer was superior to operational M47 tank for learning the track system of the tank. As a result, Denenberg concluded that the hull trainer, which costs approximately $10,000 (as compared to the mock-up which cost $27.00) does not appear to be practical since it is more expensive and does not appear to aid the training of tank crew personnel as much as the mock-up device.

In a somewhat different context, Rifkin, Pieper, Folley, and Valverde (1969) designed a job-specific simulator referred to as the Simulated Maintenance Task Environment (SMTE). Job relevant tasks were simulated to a high degree of fidelity and operations that are not encountered in the field were omitted or simulated to a lower degree of fidelity. The primary prupose of the SMTE was for proficiency testing of F-111A mechanic/technicians. However, practice was also provided for checkout, troubleshooting and removal and replacement tasks. By reducing the

fidelity of tasks that were not job relevant, Rifkin et al, were able to significantly hold down the cost of the SMTE.

Many other studies (Swanson, 1954, Besnard & Briggs, 1956; Crowder, 1957; French, Martin & Ethem, 1957; French, 1956; Richard, Moss, & Hall, 1973) have demonstrated that fidelity can be quite low in certain familiarization and procedural tasks without having any adverse effect on trainee proficiency.

Many of the applications of simulation in Air Force technical training have been concentrated in the electronics career field. In this field as well, the preponderance of studies dealing with the simulation of electronic equipment have demonstrated that inexpensive, low-fidelity devices can be quite effective. French (1957) summed up much of the electronic simulation research by stating that many of the trainers developed demonstrate that the operation of complex electronic equipment may be simulated in a simple, relatively inexpensive device without loss of the essential relationships of control and indicators.

V. PLANNING FOR SIMULATION

An important question that must be answered prior to the procurement of a simulator is what is to be simulated. As Gagne (1954) pointed out, the task being simulated should not be the equipment itself. If that were the case, then every simulator would be an exact representation of the operational equipment. It becomes obvious from a cost-effective point of view that an effective simulator should not be a duplicate of the operational equipment. The advantages of simulation are produced by only including critical task components in the simulator. Those components that are unnecessary for effective transfer to the operational job situation should not receive emphasis and should not be incorporated into the capabilities of the simulator. Since much evidence does exist that significant fidelity reductions can be achieved without compromising training objectives, the inclusion of only the critical task components offers an obvious cost-savings potential. Costs can be greatly reduced by using less-expensive simulators in place of operational equipment, and training can be improved by using the capabilities of a simulator to train job areas that impact most significantly on transfer to the operational job. Valverde (1968) has stated that although high fidelity may be desirable, the most important goal is to simulate task requirements rather than the actual job equipment. Gagne (1954) agrees that what is simulated are operations or tasks. He described tasks as interactions between man and machine or between man and his environment.

In the cost-effective approach to simulator design, the major problem becomes what tasks in the operational environment should be left out of the simulated environment? Answering that question by stating that only those tasks that produce effective transfer of training should be included, is an oversimplification. The determination is often difficult to make because the psychological requirements cannot always be specified in terms of equipment requirements (Miller, 1953a).

Many studies have indicated that how a simulator is used may influence learning and transfer of training to a greater degree than the design of the simulator itself. No matter how carefully a trainer/simulator is designed and conceived, it will fail to achieve adequate transfer of training if it is not used effectively. Utilization must extend into the entire training program. It must serve some specified purpose or criterion within the larger framework of a total training program. To circumvent some of the problems associated with inadequate specification of simulator use, Miller (1960) suggests that design recommendations should include: (a) explicit recommendation as to its proper use for training, and unequivocal statements about tasks that can and cannot be trained, and (b) the degree of training that can be expected from the recommended training equipment.

Determining Task Requirements

One of the first steps required to choosing training device requirements is a task analysis. Lumsdaine (1960) states that a training device or procedures design should start from a detailed analysis of performance requirements, specific knowledges and skills needed to meet them, and the basic characteristics of the trainees. The Air Force collects job task requirements during step 1 (analysis of system requirements) of the Instructional Systems Development (ISD) technique. There are many task analysis methods available (Chenzoff, 1964, 1965; Folley, 1964; Miller, 1953b; Smith, 1965) to help define job performance requirements. Once step 1 of the ISD approach is completed, two other steps (defining education and training requirements, and developing objectives and tests) are completed

before step 4 (plan, develop and validate instruction) is performed. During step 4, instructional media are selected. The type of instructional media selected is based upon the relationships between learning objectives and the types of learning involved and on other factors such as equipment and facility availability, production complexity, as well as costs. Tables 1 and 2 are used to derive this information.

Table 1. **Equipment/Media Relationships and Considerations**

Instructional	Media Used	Materials Production Considerations	Availability of Facilities and Equipment	Equipment Cost
1. Filmstrip or slide projector	35mm filmstrips or 2x2 slides	Inexpensive. May be done locally in short time.	Usually available. Requires darkened room.	low
2. Overhead transparency projector	Still pictures and graphic representations	Very inexpensive. May be done locally in short time.	Available. May be projected in light room.	low
3. Wall charts or posters	Still pictures	Very inexpensive. May be done locally in a very short time.	Available. No special equipment needed.	very low
4. Motion pictures (projection to groups)	16mm motion picture (sound or silent)	Specially-produced. Sound film is costly and requires 6-12 months time.	Usually available. Requires darkened classroom.	moderate to high
5. Motion picture projection as repetitive loops (8mm silent) to individuals	8mm motion picture film (silent)	Special production normally necessary. May be produced as 16mm film alone or locally at low cost and in short time.	Not normally available. Will need to be specially procured to meet requirement of instructional program.	low per unit, but moderate for groups
6. Magnetic tape recorder	¼" magnetic tape	Easy and inexpensive. Usually produced locally.	Available.	low
7. Record player	33 1/3, 45 or 78 rpm disk recordings	Need special recording facilities. Usually commercially made.	Usually available.	low
8. Display area	Trainers and training aids	May vary in complexity and in difficulty of production. Component parts easy to obtain.	Usually available.	varies from low to high
9. Television (closed-circuit)	Live presentations. Motion picture film. Videotape recordings. Still pictures.	Normally requires large and skilled production staff.	Not normally available.	moderate to high
10. Teaching machines & programmed textbooks	Programmed material	Some programs available commercially, but will normally be specially prepared for course.	Not normally available.	low per unit, but moderate for groups
11. System combinations	Television. Motion pictures. Still pictures. Audio recordings.	Complex. Probably will be done locally to meet specific requirements.	Not normally available.	moderate to high

This table is adapted from AFM 50-2, Instructional Systems Development.

Table 2. **Instructional Media Stimulus Relationships to Learning Objectives**

TYPE OF INSTRUCTIONAL MEDIA	LEARNING OBJECTIVES: Learning Factual Information	Learning Visual Identifications	Learning Principles, Concepts, and Rules	Learning Procedures	Performing Skilled Perceptual-Motor Acts	Developing Desirable Attitudes, Opinions, & Motivations
Still Pictures	Medium	HIGH	Medium	Medium	low	low
Motion Pictures	Medium	HIGH	HIGH	HIGH	Medium	Medium
Television	Medium	Medium	HIGH	Medium	low	Medium
Training Aids	low	HIGH	Medium	Medium	low	low
Audio Recordings	Medium	low	low	Medium	low	Medium
Trainer (Simulator)	Medium	HIGH	HIGH	HIGH	HIGH	Medium
Programmed Instruction	Medium	Medium	Medium	HIGH	low	Medium
Demonstration	low	Medium	low	HIGH	Medium	Medium
Printed Textbooks	Medium	low	Medium	Medium	low	Medium
Oral Presentation	Medium	low	Medium	Medium	low	Medium

This table is adapted from AFM 50-2, Instructional Systems Development.

Miller (1953b) proposes a method for determining the requirements for simulators/training devices based upon a task analysis. After the initial task analysis, agreement is reached between the task analyst and operational and training personnel on which tasks to include in training. Agreement should then be reached on what the simulator is intended to teach. The next step is to determine how well the student should be able to perform the tasks that are practiced on the simulator. It is necessary to make "degree of training" decisions in advance since many tasks will be trained to different levels of proficiency based upon their frequency of occurrence and importance in the operational situation. Following that, determinations are made about the skills and knowledges of the student population. It is useful to know what kind and how many students will be using a trainer or simulator. Similar assumptions are then made about the instructor personnel. The last step involved prior to making specific recommendations is the determination of whether operational equipment and the training device/simulator will be available side by side. The extent to which the two pieces of equipment are available side by side determines, to a great degree, how much transfer of training will take place. Once the assumptions have been agreed upon, the actual planning proceeds. The first step is to establish hardware requirements from the task analysis. Hardware usually is listed under the following headings: controls, displays, programs, accessories, and scoring requirements. The next step is the preparation of specific recommendations. Miller suggests that each item from the abstract of hardware requirements be viewed from the point of view of: (a) the task, (b) the training assumptions, and (c) the information contained in the *Human Engineering Design Schedule for Training Equipment* (Miller, 1953c). Finally, modifications and revisions are normally made after the initial recommendations are submitted.

Classification of Tasks

One of the major considerations involved in the successful design of a simulator is the determination of the tasks to be trained. Once task information is gathered, it is often useful to fit tasks into a classification scheme. Such classification schemes are often referred to as taxonomies. A taxonomy, as defined by Miller (1967), is "a means of classifying objects or phenomena in such a way that useful relationships among them are established." Gagne and Bolles (1969) list five categories of tasks that simulators have been designed to represent:

1. *Procedures*. Cockpit procedures for pilots and navigators. Consoles for control of missile firing; procedures for adjusting and calibrating electronic equipment.

2. *Motor skills*. A simulator may primarily represent a motor skill, as in the case with a gunnery simulator.

3. *Identifications*. A simulator may represent such activities as the identification of targets, of terrain features, or of emergency signals.

4. *Conceptual tasks*. Activities requiring concept using and reasoning may be represented in simulators for learning equipment troubleshooting, tactics employed in the direction of aircraft, navigation and aerial photo-interpretation.

5. *Team functions*. Some complex simulators emphasize the communication of information among members of a crew or team.

A simple modification of the above classification is presented by Lumsdaine (1960). He classified objectives into the following five categories: identifying, knowing principles and relationships, following procedures, making decisions or choosing courses of action, and performing skilled perceptual-motor acts. Many other authors (Bloom, 1956; Miller, 1953a; Gagne, 1961; Fleishman, 1961; Stolurow, 1960; Ammerman, 1966; Whitmore, 1970; Waina, 1969) have developed methods for deriving and specifying instructional objectives. An excellent discussion of the major issues and methodology involved in constructing a taxonomy is reported by Miller (1967). Although it is now commonly accepted that specification of learning objectives derived from a task analysis is highly important to the design of training equipment, this situation has been a recent development. The prevailing philosophy often held that the trainee was there to learn about his job, not to learn specific job tasks that are necessary to perform a particular job to a criterion level. However, the philosophy of training actual on-the-job skills and knowledges is gaining wide acceptance, especially where cost of training in time, dollars and operational expediency shape policy towards efficiency (Miller, 1954).

Guides and Handbooks for Training Device Selection

As with task analysis, there is a large volume of literature available in training media selection (Chambers, 1958; Miller, 1953a, 1953b, 1953c, 1954; Demaree, 1961; Uses of Task Analysis in Deriving Training and Training Equipments, 1960; Smith, 1965; Parker & Downs, 1961; Fryer, 1952; Smode, 1963). Reviews of literature dealing with determining training device design and requirements can be found in Root (1966) and Valverde (1968). These methodologies are described in detail elsewhere and will not be described here at any length. However, most of the methodologies involve the application of psychological learning principles in the design of training devices to meet specific behavioral objectives. One of the most widely used methods was developed by Miller (1953a). The principal theme of his approach is that different kinds of tasks, and different degrees of learning have different implications for transfer of training and the best form for presenting knowledge of results.

Simulators and Stages of Learning

One of the most important considerations involved in the design of training equipment is the stage of learning involved in the proposed training. Often abilities that are required early in a learning sequence may not be involved later in a sequence or perhaps to a lesser degree. One of the most significant approaches to a taxonomy based upon stages of learning is reported by Fleishman (1961). Fleishman's taxonomy is derived from a factor analysis of abilities involved in the performance of various skills at different stages of practice. Fleishman concluded that performance on a task was related to a pattern of abilities that changed with practice, and at later stages of training, specific factors arise from each task particular to the stage.

Miller (1953a) distinguishes three stages of learning. The first stage of learning is loosely referred to as indoctrinational training. This stage consists of the following kinds of training: (a) what the equipment is supposed to do, (b) learning equipment nomenclature, (c) equipment and object locations, (d) search and scanning methods, (e) control-display interactors, (f) control-display directional relationships, (g) control-display ratio, (h) control-display ranges, and (i) attitudes towards task and learning the task. Since the early stages of learning characterized above are highly verbal, equipment considerations are not usually of great importance. Thus, there is very little gain from simulation during the early stages of learning.

In the middle stage of learning, the trainee moves into a much more complex phase where he

must refine and coordinate movements, perceive larger blocks of information, and progress to a more automatic level of skill. The middle stage consists of (a) perceiving larger blocks of instruction, (b) perceiving signals in advance of initiating motor activities, (c) coordinating motor movements, (d) learning serial motor responses, (e) responding to rates of stimulus movement, and (f) reduction of confusion and integration of habits into time series. During this stage of learning, simulation has proved to be quite beneficial, particularly when simulation practice is integrated with practice on the operational equipment.

The next stage of learning (high degrees) cannot be precisely differentiated from middle degrees of learning, since many of the distinctions are slight and only a matter of degree. However, the following kinds of training are encompassed by the term "high degrees of skill:" (a) automatized habits, (b) anticipatory response and time intervals, (c) double checking of perception and action, and (d) generalization to special situations. As trainees move into the high stages of task learning, much of what has been learned becomes automatic and response habits tend to become restricted to specific stimuli. During this automatic stage of learning, simulation, especially high -fidelity simulation, is highly effective. However, a point is reached where simulation is no longer profitable from a cost-effective point of view in relations to practice on the operational equipment. It is often difficult to determine when simulation becomes less efficient than using operational equipment. However, as a task becomes more complex and involves high stages of learning, the use of simulation is usually less appropriate than using operational equipment.

A less-detailed description of the types of training associated with the various stages of learning are described as: (a) indoctrination training, (b) procedural training, (c) familiarization training, (d) skill training, and (e) transition training. Research has found that certain types of training devices may be appropriate for specific type of training associated with a particular stage of learning. Although recommendations are implied for the use of different training devices for each behavioral category, Miller (1953a) warns that the assumption should not be made that a different training device is required for each behavioral category. Suggested types of training devices to be used for the various stages of learning are listed in Figure 3.

Gagne (1954) feels that the proper use of a simulator is during the late stages of learning and also for skill maintenance. As has been pointed out by other researchers, the use of simulation could prove to be highly inefficient and expensive during the early stages of learning. During this stage, it very often suffices to use inexpensive training aids, charts, etc., to accomplish the training objectives. The only exception to this general rule is when learning relatively complicated motor skills (Gagne, 1954). For motor learning, the extant evidence points to the need for highly accurate task simulation almost from the very beginning of training.

The important consideration becomes how to design a simulator to take into account the various stages of learning. Usually when learning a motor task or most tasks in general, the initial learning process involves a great deal of verbal mediation. As learning progresses into later stages, the actions of the trainee become more automatic. Effective simulator design must take into account the different abilities required at various stages of learning. In other words, design consideration should emphasize flexibility. The simulator should be able to accommodate trainees at all stages of learning. It is obvious that in early stages of learning, especially those tasks involving motor skills, only very rough discriminations are required of the trainee. As learning progresses, the actions of the trainee become smoother and the discriminations become finer. Thus, only a very rough approximation of the operational equipment is normally necessary in the early stages of learning. Later on, as the task details to be learned become more complex, the requirement for greater fidelity increases.

Fidelity and Stages of Learning

What degree of fidelity must be used for each stage of learning? No firm answers are available to this question, but much evidence has been collected to aid those who are responsible for making such decisions. During the early stages of learning, a high-fidelity representation may tend to confuse a trainee because of the rapid presentation of a complex sequence. Similarly, the same situation may not be challenging enough to the student who has progressed to a high level of skill consolidation. The relationship between the different types of fidelity and stages of learning is presented in Figure 4 (Kinkade & Wheaton, 1972). It seems that the need for fidelity, especially

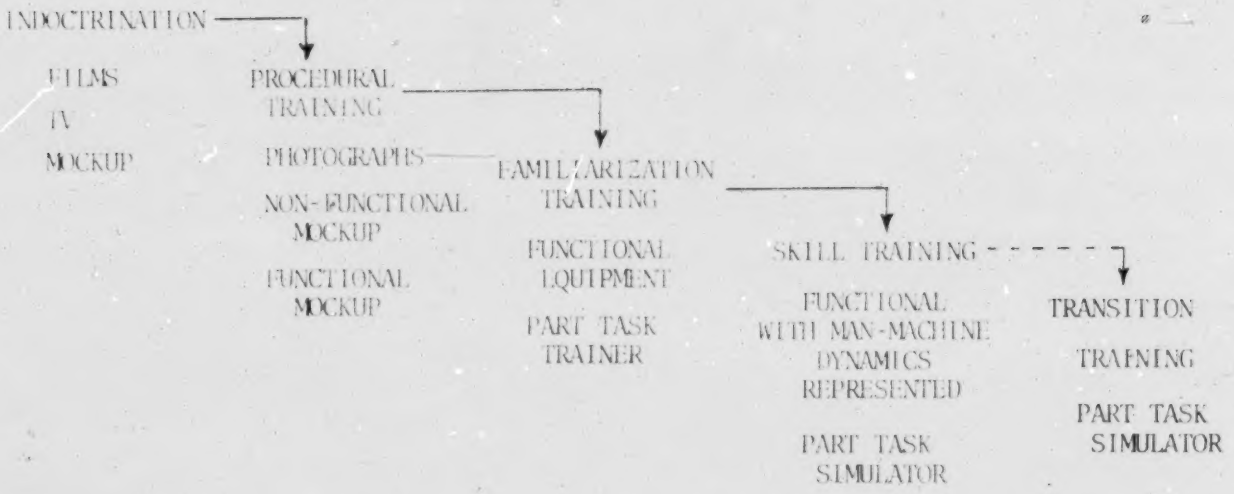

Figure 3. **Types of training devices associated with stages of learning.** *(adapted from Kinkaide & Wheaton, 1972)*

environmental fidelity, increases as the skill level increases. The initial stages of learning require very little fidelity, whereas, as the stages of learning progress, the need for simulation increases and then plateaus.

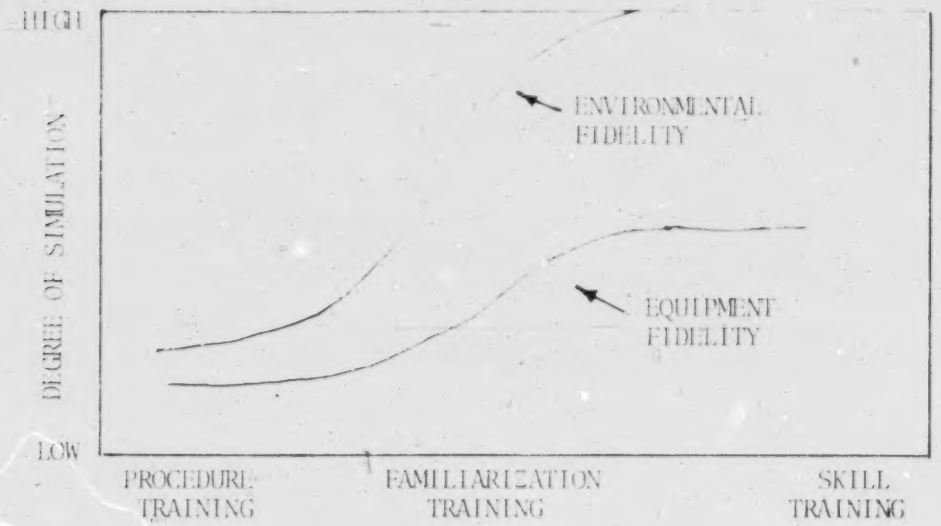

Figure 4. **Relationship between environment fidelity, equipment fidelity, and stages of learning.** *(adapted from Kinkaide & Wheaton, 1972)*

VI. PRINCIPLES OF SIMULATION

Although some research has been conducted in very specific situations comparing one type of simulator/training device with another, or with the operational equipment, general principles for the effective application of simulation are still largely hypothetical. Most of the principles that have been developed apply largely to flight simulation, and not directly to simulation for technical training. However, for the sake of comprehensiveness, and since there is some overlap, some flight simulation principles are included. Very little hard scientific evidence has been collected to support or refute the hypothetical relationship between fidelity, cost, and transfer of training developed by Miller (1954). The challenge put forth by Gagne in 1954 to "discover principles which may be applied to training devices in such a way as to make them more efficient than haphazard on-the-job practice" still beckons. Many authors have drawn conclusions based upon their research about fidelity, cost, transfer of training, selection of simulators, design considerations, motivational factors, etc. Training programs and training media are obviously quite complex and those responsible for making training program and media decisions should not view guidelines and principles as hard-and-fast rules with universal applicability. They should, instead, remain cognizant of the shortcomings of guidelines and principles and consider the uniqueness of many training situations.

Much knowledge about the principles of simulation has been collected painstakingly and has been reported by such researchers as Baker and Warnick (1970); Gagne (1954); Miller (1953d); Smode, et al (1963); Demaree (1961); Biel (1965); Kinkade and Wheaton (1972); and Lumsdaine (1960).

One of the most comprehensive compilations of principles that can be applied to simulation is reported by Miller (1954). His principles are categorized under basic principles, principles that apply to the first, middle, and high stages of learning and principles that apply to transition training.

Principles for the First Stages of Learning

During the indoctrinational phase of training, classroom presentations involving verbal statements by instructors, written statements, diagrams, or examples will generally suffice to give the student a general picture of the job purpose, and the relation of immediate training objectives to later training objectives. Equipment considerations are irrelevant to this phase.

Whether the ultimate performance of the task is continuous or non-continuous, the early learning tends to be of discrete non-continuous S–R segments in which both the stimulus and the required motor response or decision are verbalized or conceptualized.

During all stages, but especially in the early stages of learning, group morale and individual effort rests on having rather clearly defined goals in which the individuals participate.

The new student should have an opportunity to see both operational and regular training equipment in action, preferably when operated by well-motivated individuals.

The student should *overlearn* the nomenclature of the displays and controls of the equipment. This process can be initiated by the use of pictures and diagrams, and be continued with no more than non-functional mock-ups of the operational or training equipment. It is inefficient to begin practice on complex training devices until nomenclature appropriate to training and operations has been *overlearned*.

The student should develop facility in the location of displays and controls of the equipment before beginning time-stressed performance of the task. Pictures and non-functional mock-ups will be adequate for this phase which would, in practical situations, be combined with the learning of nomenclature. In order for locations to be learned to a degree that a work object can be located by the student without extensive search for it, it will be necessary for him to be in a rough physical replica of the work space in the training (or operational) device on which he will next get training. For motivational purposes, this training should take place whenever possible in the operational device when it is undergoing repair or is otherwise not in use.

The student should be encouraged and required from the very start of task performance training to develop perceptual habits of search and scanning which will be operationally effective, even though they may somewhat delay the learning of tasks which in themselves require only restricted perceptions.

In the early stages of training, the student should highly learn what controls affect what display features and the gross interactions (which will include directional relationships) between any

given control and the several display features it modifies. Simple functional mock-ups will be adequate not only to demonstrate the control-display interactions, but to allow the student practice in making elementary checks between his control movements and indicator movements. It is sufficient that the locations of displays and controls and their directional characteristics in this simple functional mock-up simulate those in the complex training device. The student should not get a high degree of practice on such a simple device (i.e., practice should be stopped when the student shows no hesitancy in knowing where to look for display consequences of a control movement).

If the operational task is a complex continuous feedback skill involving long feedback delay, we hypothesize that the student's learning of the directional relationship would be facilitated by a device presenting rapid feedback. Since the directional relationships should be quickly learned with such a device, we further hypothesize that practice could be stopped before the student developed such dependencies on immediate feedback that he would be subject to severe interference effects when beginning practice on a device (training or operational) which presents the appropriate feedback lag.

In order to reduce the risk of teaching faulty anticipations in a continuous task with feedback lag, the display program presented to the student in the early stages of training might consist of a series of *discrete* misalignments of displays which the student detects and can correct by suitable control movements. This tentative recommendation involves the transfer from an artificial discontinuous situation to the continuous kind of task performance related to the operational situation. Experiment evidence is needed on this point.

In general, for the early stages of learning a continuous task, engineering simulation may be rough with respect to display-control interaction. Direct mechanical linkages might be quite effective. Control pressures should be great enough to damp out adventitious movements by the student. However, in line with the warning given previously, a general caution should be stated: the more practice given, the greater the degree of engineering simulation (up to a point) which will be beneficial.

The student can be induced to accept less realism in a training device, to the extent that indoctrination is provided him.

Principles for Middle Stages of Learning

Early in learning a complex task, the cues necessary and sufficient for making the decisions and response actions of a task might be abstracted and presented as such to the student. Some transition training to the actual operational conditions would be necessary in order for the student to learn to differentiate guiding cues from irrelevant external stimulation. (Experimental verification is badly needed on this point.)

The training device need not simulate cues in finer perceptual units than are essential for the student to discriminate in operations. On the other hand, the perceptual units should be no coarser than required in operations.

Since a training device can only approximate (at sharply increasing cost) the many environmental stimuli which can act as "noise" to the student in the operational situation, it is suggested that during middle stages of learning, training on an artificial device be alternated, from time to time, with practice on the operational device. Such a practice method also should increase motivation (assuming student acceptance of the training device).

Whenever the performance of perceptual anticipations is done under different environmental conditions, or different subjective conditions of the subject, the anticipation will be subject to error. This error will tend to be less if the student has learned standard supporting series of responses, preferably cyclic or rhythmic, in association with the perceptual anticipation. It does not matter if these responses are or are not intrinsic to the perceptual task.

Where sustaining cues for time estimation are present in the operational situation, they should be introduced in the training situation when the student is at the stage where he begins to develop anticipations based on perception of time. Engineering simulation of such cues can be rough. For example, in most flight training devices, assuming that "engine noise" is a sustaining cue for time estimation, it would be sufficient for the "engine noise" to consist of a continuous recording, the volume of which is tied directly in with throttle manipulation (much as the volume control on a radio), and which could be turned off by various controls which normally cause engine failure or shut-off.

Time relationships of both continuous and discontinuous tasks should be simulated

(engineeringwise) as soon as the student is at a stage of practice where he is responding to rates directly from the environment or from equipment feedback. Ideally, the degree of engineering simulation would be within the mean standard deviation of the mean anticipations of experts at the task.

During the stage of learning when the student is *beginning* to acquire simultaneous coordination of motor movements, the training device should have *substantial control loadings* (apart from considerations of what these loadings simulate). If such additional loads are introduced, they should be removed soon after moderate simultaneous coordination ability is shown.

The *relationship* of loadings of different controls used simultaneously in coordinated movements should be maintained engineeringwise, between training and operational device for the above stage of learning (provided that there is a discriminate difference between them). The absolute values are somewhat less critical.

In the middle stages of learnings, control loadings on the training device should be somewhat less rather than greater in absolute amount than they are in the operational equipment. (Unless, of course, the operational loadings tax response capacity.)

During the phases in which the student is acquiring *coordination* of motor responses, he should at least be given occasional opportunity to practice on the operational equipment. Such practice will provide a basis for *learning to transfer* his skills from the training device to the operational device.

Rather than attempt to convince the student that the training device and the operational device are identical in their task demands, special effort should be made to help the student differentiate their characteristics. Much of this differentiation can be done verbally by the instructor. This recommendation is especially pertinent where practice sessions on the training device and the operational device are given concurrently.

When a student must be trained to learn a discontinuous series of responses so that they become automatized, we hypothesize that the student should: (a) begin learning by self-pacing, then (b) be introduced to slow pacing of the task as soon as the sequence can be formed at any rate with a very few errors or none at all, then (c) be given increased pacing of the task to operational requirements (not, however, increasing this pacing at such a rapid rate that a large amount of errors develop), and finally (d) be given task-pacing beyond that required of operations.

In learning a discontinuous series of responses to the point of automaticity, the student should be encouraged to make pre-positioning movements for control activity as rapidly as possible. (This recommendation holds even for the earliest stages of learning to operate the controls.)

To the extent that serial responses, when well-learned, depend upon rapid pre-positioning, the locations of the controls should be simulated in any device used for task performance.

A well-learned response series becomes performed as a function of the occurrence of previous responses in that series. To interrupt or disturb one of the responses in that series risks disruption of the entire series.

Where there is to be transfer from a training device to operational devices which differ discriminably in temporal or spatial requirements in which a response-cued series is to occur, the student should not be allowed to overlearn the response-cued series in the training device to such an extent that the verbal mediation phase of guiding his responses has dropped out. This is especially true of tasks which are task-paced rather than self-paced, and of tasks where there is a heavy perceptual load in operations.

Whatever cues carry to the student, the representation of target motion, the range of motions represented should be greater than the ranges of motions which the student will meet in operations.

During that training period when the student is learning to make adjustments of the "cursor" motion relative to target motion, the characteristics of the cursor with respect to timing must be closely simulated.

To the extent that the student must learn anticipatory behavior, the time relation both of the target motion and of the control-to-cursor movement within the training task should simulate the time relationships within the operational task. If the task has continuous error feedback, it will be easier for the student to adapt to changed temporal conditions than if the feedback is momentary or intermittent.

If the learning of tracking of non-repeated tracks has been to no more than a moderate degree, the simulation of time-space values exclusive of range, in target programs (as well as

cursor characteristics) will be more critical for high transfer than if the learning had been carried to a high degree. (This principle should hold only where the task involves tracking of non-repeated tracks such as in operational gunnery, bombing, and navigational problems.)

Practice in a time-critical task should include activities which immediately follow the critical performance of the task.

Principles for High Stages of Learning

Habits should tend to become increasingly automatized under the following conditions:

1. Highly repetitive practice (including serialized response patterns).

2. Practice under heavy informational loads, or in low signal-to-noise ratios.

3. Practice under strong anticipations, demands or anticipational activities (including strong "motivation" and "anxieties").

4. Practice at speeds which tax the student's momentary S–R capacities.

When habits are becoming automatized, there must be greater degrees of engineering simulation for effective immediate transfer of training from trainer to operations. Relatively small changes may produce relatively large decrements in the transfer situation. If, however, concurrent training has been given on the operational device, this "training for transfer" may reduce the absolute requirements of engineering simulation in the trainer.

When *continuous* tasks are becoming highly automatized, it is essential to copy the programs of displays requiring essential discriminations. The location, direction of movement, and "play" of controls should be copied. Control pressures and control-display ratios will be somewhat less critical than the copying of the characteristics lags between activation and display response. Sensitivity of the trainer may be slightly, but not grossly, greater than the operational equipment unless critical expectancy patterns are involved in operations. The student should not be led to "expect" that this equipment can perform responses which, in fact, it cannot do.

When *discontinuous* tasks are becoming automatized, especially if the task heavily loads the student, both displays and controls should be highly simulated from an engineering standpoint. The location and direction of movement should be copied. If the control action is all or none, some variation may be permitted in control "pressures" in the broad sense of that term. Time delays feedback must be simulated (engineeringwise) to the extent that the feedback is an action signal for the next response. If the response sequences are task-paced, the pacing of the training device should copy those of the operational device or preferably be somewhat *faster*, especially if the student will have heavy load or stress in operations.

If smoothness in tracking response is an important requirement, training in the higher stages of learning should be for the development of long-term anticipations.

The less the freedom of choice after any moment of commitment, and the greater the time or activity between point of commitment and zero error between target and cursor, the more difficult the anticipation, and once learned, the more the anticipation wil break down if different motion parameters are introduced in target or cursor.

Other things being equal (which they usually are not), where there is no psychological lag between control activation engineering simulation of equipment functioning may be somewhat less precise than where there is appreciable lag between control activation and display movement.

If the operator is able continuously to anticipate the change in the target motion with enough lead to permit his anticipatory motor patterns to keep pace, he may approach zero error (example: tracking a sine wave).

To the extent that the target motion is only probable, the operator's perceptual anticipations will be limited to ranges of probability. The disadvantage of this indeterminacy may be offset by greater maneuverability of the cursor than of the target, and by the operator's control, through anticipations, of the cursor (example: jet fighter attacking a slow bomber).

The later trials on a complex training device (before all training is given on the operational device) might, with advantage to the student, incorporate wider ranges of target movement with respect to velocities, accelerations, and spatial patterns than are found in operations.

With respect to direct transfer to *predictable* target and cursor motions, these stages of high degrees of learning should simulate with great accuracy the time values of the operational programs of target and cursor motion.

More complex decision-making requirements should be programmed into the training situation for higher stages of training than are usual in operations.

During the higher stages of learning, emergency procedures should be "overlearned," that is, learned to so high a degree that they can be unreeled with little mediating verbalization. But the student should also be able to perform emergency procedures on the basis of verbalization of cues, decisions, and actions so that when necessary he can respond rationally to special situations which require modification of a machine-like sequence of activities. Special forms of practice will be necessary to maintain these verbal sequences while the motor sequences become automatized.

The purpose of training should not be to produce stress in students but to reduce it in criterion situations. Therefore, stress responses should not be "conditioned" in the training situation, unless continued practice can be given which leads to habituation and the elimination of such stress conditions in the student. (This admonition is particularly appropriate to instructors.)

Less engineering simulation in the training situation will be required to produce stress experiences in students who are well motivated to learn, and perform the operational job than in students who are less well motivated.

It is probably more efficient to teach the student from the start of training to scan his task environment for cues that emergencies exist, rather than to training for emergencies as a final or separate order of tasks.

Principles for Transition Training

Merely training on isolated differences between two tasks in transition training is likely to produce little transfer between them. The old response context may support the old habits in operational conditions.

To the extent that specific responses are supported by a context of cues and responses, learning new responses to old cues in other than the new task context may not transfer *reliably* to the new context situation unless very special conditions are met such as low-signal-load and plenty of time for the student to recall and instate the new response.

The student will be more successful in learning and performing the new task or job in transition training if he has learned and transfers from the old job the habit of double checking his discriminations and motor responses.

If the "new" equipment has critical maximum or minimum values in operating functions (called "critical discontinuities") which differ from the "old" equipment, these differences should be especially emphasized in transition training, and this training should be given in the new task context.

If the student is expected to perform the new task at high levels of skill immediately after he concludes transition training, then the time values and lags of the training and operational tasks should be simulated very precisely.

If the student will have opportunity for familiarization practice on the operational equipment he is being transitioned to before he is expected to perform the new task at high levels of skill, then for tasks not differing greatly in time and load requirements a relatively small amount of practice on the operational equipment itself will generally enable the transitioned operator to "get the feel" of what the equipment will do. If more rapid discriminations decisions, and actions, or greater "channel capacities" are required in the new task, the student will need extensive additional transition training on what should be treated as a new task—not an old task in modified guise. Thus, the degree of engineering simulation will have to be greater for such tasks.

If on the new task the coordinated and integrated action of a crew or team is involved, and especially where rapid sequences of interlocking discrimination, decisions, and actions are required with small time tolerances, it becomes highly important that they be transition trained in the context of the informational loads they will have to handle.

Kinkade and Wheaton (1972) have also compiled a relatively comprehensive list of design recommendations for simulators/training devices. Their list of recommendations is somewhat more simplified than Miller's and is divided into general recommendations, recommendations for equipment fidelity, recommendations for environmental fidelity, and principles of time compression.

The following design principles are recommended under general principles of design:

1. Design for unusal use patterns
2. Design for easy access
3. Design to ruggedize the training device

4. Design for reliability and maintainability

5. Design for simplicity

6. Design to provide efficient conditions for learning

7. Design to teach specific tasks

8. Design to provide proper feedback

9. Design for practice of difficult components

The next group of principles listed by Kinkade and Wheaton is concerned with equipment and environmental fidelity. As was previously discussed, equipment fidelity refers to the degree to which the simulator duplicates the physical appearance and the "feel" of the operational equipment being simulated. Whereas, environmental fidelity refers to the degree to which the simulator duplicates the sensory stimulation that would be received operating the operational equipment in the field. The following design recommendations are offered by Kinkade and Wheaton concerning equipment fidelity.

1. Cabin restraints should be represented accurately, but not if they interfere with the learning process.

2. Realistic instrument design layout is important, however, minor deviations in size and shape have little effect on transfer.

3. Controls in the forward plane, frequently used controls, and critical controls should be placed carefully. Minor deviations may be made for controls requiring visual guidance.

4. Reasonable attention to factors affecting control feel is sufficient for training simulator.

5. Minor deviations in control-display ratios have little effect on transfer.

The design recommendations for environmental simulation are as follows:

1. The degree of environmental fidelity required may be determined on the basis of psychological fidelity.

2. In a complex task, transfer of training may be degraded by an abstract representation of the visual world.

3. High environmental fidelity is required when the actual tasks require a difficult distinction be made between different stimulus events.

4. Where the operator must learn to compensate for motion in the actual task, motion cues should be provided although high fidelity is not demanded.

As has been discussed earlier, one of the important advantages of simulation is the capability to manipulate the passage of time in the accomplishment of some operational sequences. Depending on the stage of training involved, it may be advantageous to speed up or slow down an operational sequence to facilitate training. The following "considerations" about time compression and expansion are offered by Kinkade and Wheaton:

1. Time scaling should be based upon student skill level and training objectives rather than realism.

2. Time should be compressed when critical events occur slowly in the operational system. Students should not be time-stressed, however.

3. Time should be expanded when events occur rapidly in the operational system.

4. When operator speed is desirable, time compression is advisable to increase problem difficulty.

5. Time "freezing" is often desirable when stopping an operational sequence would help improve learning.

Demaree (1961) cites five principles of training device design that were developed as a result of research on the malfunction and circuitry (MAC) trainer. Although the principles deal with the broad category of training devices, simulators and their design implications are specifically included. The principles are as follows:

1. Work habits which are opposed to efficient job performances should not be reinforced by a training device.

2. For training devices which provide practice of troubleshooting skills, there is little advantage to be gained in realistic simulation of previously learned acts or performance segments.

3. For the practice of any sequence, transfer to performance on the actual equipment is increased if each step of the sequence is represented by an overt action of the trainee.

4. The transfer and retention of skills acquired through practice or proceduralized tasks on a trainer increases as a function of fidelity of simulation.

5. In a procedural trainer which provides step-by-step instructions, more efficient learning of the instructions will result if these are presented one at a time rather than as a set.

Some of the principles set forth by Demaree may appear to be contradictory to other established principles, especially principle 4, page 25. As stated, it would appear that corresponding increases of fidelity produce corresponding increases of skill and transfer when practicing a proceduralized task. However, Demaree does go on to clarify the use of the term fidelity as meaning the degree of realism used to represent a task. Thus, a photographic mock-up with dummy dials and indicators could provide the desired realism for successful learning of a proceduralized task.

Biel (1965) summarizes the conditions that must be considered in the design of a training device/simulator. The major factors involved are the type of task, stage of learning, required proficiency, initial skill level, and the interactions among these variables.

Lumsdaine (1960) provides a rather comprehensive list of general principles, principles for determining device requirements the design of devices suitable for certain training objectives, and procedural guidelines for designing certain types of devices. Although many of the principles stated by Lumsdaine have been reported in other sources, some of the principles dealing with inexpensive simulation are helpful. Lumsdaine states that for complex procedural and malfunction diagnosis tasks, a combination of simulated and real components with special circuitry to provide feedback may provide a relatively inexpensive substitute for operational equipment.

In their discussion of simulation principles, Baker and Warnick (1970) feel that transfer of training can be enhanced by adding situations to the simulated environment that are dissimilar to the operational environment, such as knowledge of results, increased crises, time compression, etc. They also state that attention must be focused on the degree of operational and motivational similarity. Operational similarity refers to how the output of the simulator is affected as the result of operator behavior in relation to the real situation and equipment. Motivational similarity, on the other hand, refers to the similarity in feeling or attitude on the part of the trainees. This concept of trainee acceptance of the training simulator has received a great deal of attention from many researchers. It seems to be apparent that the training value of any simulator can be significantly decreased if the trainees do not feel that the simulator is an accurate representation of the operational equipment. Thus, when a cost-effective approach to simulator design is used, careful attention must be paid to motivational similarity. Even if maximum attention is paid to this factor, other factors, such as the training program, the training management, the attitudes of the instructor, the scheduling, etc., may be at work to sabotage the training value of any simulator. As has been emphasized throughout this report, a simulator cannot be built in isolation. To be effective, a simulator must be part of the entire training program and serve a specific purpose within the context of the entire training program.

Several basic principles of simulation that have implications for design of cost-effective simulators are discussed by Gagne (1954). He contends that: (a) fairly radical departures from physical similarity can produce high degrees of transfer from a simulated to an actual task, (b) the optimal function of a simulator is in the late stages of training and in skill maintenance, and (c) if a simulator is wholly designed for use in performance assessment, it is not likely to be optimally designed for training, and vice versa.

Although many principles of simulation have been formulated, there are still no hard-and-fast rules for the design and utilization of simulators. Many training situations that can profit from simulation are different to the extent that varying levels of fidelity are required to maximize cost-effectiveness. In other situations, fidelity may be secondary to the increased benefits that may be accrued from deliberate departures from realism. Enough experimental evidence exists to state some principles for the cost-effective design of simulators, but the variability of training situations dictates that the most effective decisions about simulator design be based upon something more than past evidence gathered from training situations that may not be generalized. Optimal simulator design decisions should be based upon experimental evidence gathered from transfer of training studies. Once the relationship between training on a simulator and actual operational performance are understood, then knowledgeable decisions about simulator design can be made.

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